Error parameter estimation of a three dimensional tool path measurement device

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Executive summary

The first of September 2005 I left the Netherlands, with a lot of enthusiasm, to be a guest at Keio University for a period of eight months to write my master thesis there at Prof. Mitsui's lab. Previous to that a Japanese language and cultural course had been organised in Berlin as part of the exchange programme. I have had a fantastic time in Japan and it was an experience never to be forgotten. The research assignment was a great success and the scarce hours of free time were well made use of.

The constant desire to be able to manufacture with higher accuracy and the general acceptance of multi-axis machine tools are the main drivers for my research assignment.
During a machining operation of a NC-machine a tool removes material from the workpiece. Multi-axis machine tools can perform three dimensional tool paths. The combination with the desire to machine with high accuracy calls for the necessity to be able to measure a three dimensional programmed tool path before the actual machining operation. Because it is evident that an displacement error or displacement inaccuracy is automatically copied onto the workpiece when machining.

My research assignment was to find the error parameters that have the most significant negative influence on a three dimensional measuring device. This device is built up of links and rotary encoders that measure angular displacement. The Rotary Encoder Link Mechanism (RELM), as the measuring machine is called, was designed, developed and patented by Prof. Mitsui's lab. The unique aspect of this machine is that is potentially has the possibility to be an economical tool to measure three dimensional tool paths. During a measuring sequence the RELM is coupled to a NC-machine and follows the displacement of the tool head.

During the period of eight months I made a complex algorithm that describes the behaviour of the RELM. The algorithm includes the dimensional errors and the bearing roundness errors of the RELM. The developed Error Parameter Mapping principle made it possible to use the whole measuring range of the RELM with a measuring accuracy of ± 5.03 μm. Coming from an accuracy of ± 349 μm this is an improvement of the factor 69.

Exchange student life

Laboratory

The welcome I received when arriving in Tokyo was exceptional. The members from the lab had come to Yokohama to pick me up from the bus station. This hospitality immediately made me feel welcome and I was a bit sorry I was so exhausted from the flight. We all travelled from Yokohama to Hiyoshi and there they brought me to the Keio International Student House. They helped me check in and afterwards we went to the University, which is only 5 minutes by foot, where I met with Prof. Mitsui. I was of course very exited that I had finally arrived in Japan and because everybody was so friendly and helpful I felt at home right from the start.

Within the first few weeks we all got to know each other. Welcome parties had been organised and on these occasions the delicious food together with the drinks made a fantastic atmosphere. It was obvious that people were enjoying themselves. A lot of laughter, anecdotes and questions about each others culture.

The members in the lab were very friendly and helpful whenever there was a question or something they could help with inside or outside the University. A lab member coming along to the central administration office a few stations from the University to help you get everything organised is one of many examples.

The Mitsui laboratory held twelve people and then of course the professor himself. The best part was that the office of Professor Mitsui was in the same area of the other students. The big advantage was that the communication lines through out the whole research project where very short. Meetings on regular basis and instant feedback made the use of time efficient.

The working day generally started somewhere between 9.00 and 10.00 am. The time of arrival generally got closer to 10 am as the weekend came closer. My ritual would be to make some coffee, I was the only one in the lab who would drink coffee, check my mail, replay the most urgent ones and get started. At lunch time most people would eat what they had brought from home, but there was a group of four that would have lunch in the canteen and this is also what I did. The canteen was outstanding. Having a regular menu of mostly warm small dishes that together combine a great lunch they also had changing specials. In the afternoon I would generally have a instant nodule soup, much better quality than the ones I had on occasion back home. For supper I would walk to a bento shop, a take-a-way place, close by the university order something there and come back to the university. Back at the university I would eat my meal watching the Dutch news on my lab top. There was absolutely no issue of at what time you were allowed to go home and in my experience also so social pressure of any kind. Personally I get more productive at the end of the day, so the first few months I would leave at around 9.00 pm and towards the end this would be closer to 11.00 pm. Occasionally staying until deep in the night.

I have absolutely no negative feeling what so every about the working hours. It came naturally as you adjust to the life in the lab. Other lab member also put in a lot of hours, depending on deadlines, presentations, paper submissions and so on. I went to Tokyo for a mission and I wanted to give it my absolute best. I found that when I exactly knew what I had to do I would stay late and work to get it done as soon as possible. This gave a great sense of achievement and a lot of energy. I noticed that being uncertain of what to do next with the research had more impact on the ability to make long days. So you could say that when I stayed in late I generally felt better, because the research was progressing.

The Mitsui laboratory is a very pleasant environment to work in. The research assignment made good progress right from the start and as mentioned before I felt very welcome and accepted. This all contributed to the unforgettable experience of being a guest in Tokyo for a period of eight months. I have learnt a great deal from the research project and because of the progress and the atmosphere it made the whole assignment a lot of fun.

When my lab friends when on a trip, in the weekend or during the weekends, they would bring something special to eat from the region they visited. This is a very nice part of the Japanese culture and an interesting way to get acquainted with food from different regions.

Towards the end the welcome parties for the new lab members together with my farewell parties where again a lot of fun. In the last week before I left the lab members had something extra special organised. They had rented a house close by the sea, where we had a barbeque that lasted throughout the night. I thought this was the most special surprise they could have given me. Before I finally left I received tons of gifts and they also waved me of on a Sunday morning at 5.30 am on my way to the airport.

I consider myself very lucky to have been a part of the Mitsui lab. I hope there is a chance that I get to meet them all very soon.

Outside Laboratory

Before I arrived in Japan I had sent a letter to the Dutch social community in the Tokyo area. I became a student member and because they organised a lot of things this was an ideal way to meet other people and get some good trips on enjoying life outside the university.

Through this channel I heard about a business plan writing competition. Fifty people with more than fifteen different nationalities, also including the Japanese nationality, worked in teams to work on individual real life business cases of foreign companies that wanted to take there business to Japan, or extend there market share. The programme started by having lectures on Saturday's and learning about doing business in Japan and on how to write a winning business plan. This was a fantastic environment of young people from all over the globe who had been living in Tokyo of a while and who wanted to learn more about doing business in Japan. Through this programme I met a lot of interesting people. In the end our team won the second prize for our business plan winning a round trip ticket from Japan to the US.

Reinout Swane a friend of mine from Delft arrived in Tokyo a month after I had arrived. We had a lot of fun together checking out the night life and generally having a lot of fun in the remaining free hours. He also was part of the DeMaMech exchange programme but did his assignment at the Tokyo University. Except from having a lot of fun it was also very nice that we could discuss the different issues encountered in our research.

Tokyo is of course a very big city and needless to say there is always something going on. Possible tips are probably already outdated when you read this, so here follow some very basic ones. Meeting people is by far the best way to find out where you have to go to, what you have to see, where you have to eat and so on. There is a magazine called the Metropolitan which is made by foreigners living in Tokyo where you can find some good tips on various different subjects. Reinout and myself called the 'Tokyo City Atlas' the bible. This small book contains detailed maps of Tokyo and an absolute most have to carry around with you when ever you have to find your way, and that is a lot more often than you think.

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Technical report

Maarten Boelens

Introduction

In the world of manufacturing there is a constant need for machining with higher accuracy. Multi axis machine are able to follow more complex tool paths and these machine tools are becoming more widespread. When requiring high accuracy products is it of evident importance that the followed tool path agrees with the desired machining operation. An error in the tool trajectory is automatically copied onto the workpiece. Because of the introduction of multi axis machine tools these tool paths can have complex three dimensional shapes. There is no economical feasible way of measuring three dimensional tool paths with high accuracy. Current measuring devices each have there own speciality and some are restricted to small measuring ranges. As indicated no measuring device can perform all the possible measuring sequences with high accuracy.

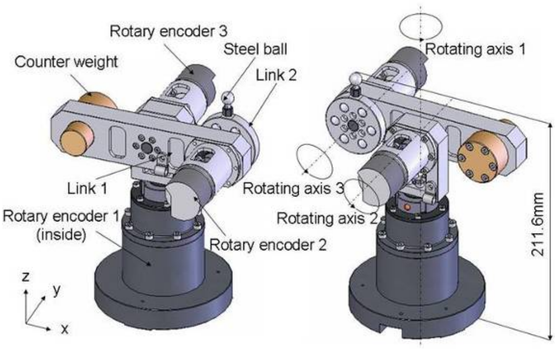

Figure 1. Rotary Encoder Link Mechanism

The Rotary Encoder Link Mechanism

The Metrology of Manufacturing lab of Prof. Mitsui have designed and patented a three dimensional measuring device to measure three dimensional tool paths of milling machines. The **RELM, Rotary Encoder Link Mechanism**, is built op of links and rotary encoders that measure the angular displacement. A high precision steel ball at the end of the last link of the RELM is magnetically connected to a machine tool by placing a magnetic cup in the tool holder of the machine tool. The RELM has three rotary encoders enabling the RELM to follow any three dimensional tool path preformed my the multi axis machine tool.

During a measuring sequence the rotary encoders of the RELM measure the angular displacement of the links. To be able to calculate the centre position of the steel ball the information of the rotary encoders are combined in an algorithm with the dimensions of the RELM.

Objective

In an ideal world the dimensions of the RELM would be the exact same dimensions as designed, the bearings would be ideally round, the spacing of lines inside the rotary encoders would be ideal, etc, etc. Unfortunately in the real world this is not the case and all these differences with the ideal situation have impact on the end accuracy of the RELM. All these different have influence on the accuracy because they influence the behaviour of the RELM. The difference between the real behaviour and the designed behaviour of the RELM can be described with error parameters. These error parameters are used to correct the expected designed behaviour of the RELM and therefore make the RELM a more accurate measuring device.

My research assignment was to find those error parameters that have the biggest influence on the accuracy of the RELM and to make a new algorithm that uses these error parameters to calculate the position of the centre of the steel ball.

Dimensional & Bearing inaccuracy

As found in literature the dimensional differences between reality and the designed dimensions can account for more than 95% of the inaccuracy. Therefore the most logical first step was to try to find the real dimensions of the RELM.

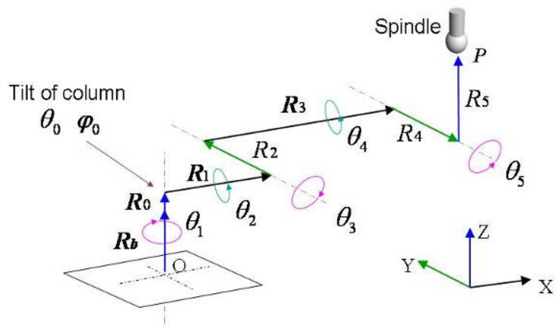

Figure 2. Line Model

Making a model for the behaviour of the RELM resulted in a mathematical model of six lines and twelve parameters. The twelve parameters consist of the six lengths of the line pieces together with six parameters that describe the radial angle of the line pieces relative to each other. The relative axial angles are set to 90°. This model can exactly describe the behaviour of the RELM when only taking the dimensional error into account.

An equation of twelve independent parameters can only be solved with a minimum of twelve answers of that same equation. This creates twelve equations with twelve answers and the parameters can be solved using the Least Square Method. For our algorithm the answers necessary are different positions, in a three dimensional space, of the steel ball of the RELM. The different positions used to solve the error parameters are called calibration points. Using these calibration points the error parameters can be determined after which any tool path measured by the RELM can be calculated.

De designed algorithm using only dimensional error parameters showed a dramatic increase in the accuracy of the RELM. With the use of these error parameters the accuracy went form ± 349 µm to ± 5.10 µm, increasing the accuracy by a factor 68!

In reality a bearing is ideally round, but in reality this is not so. The next step was to add the roundness inaccuracy of each bearing to the algorithm. Each bearing was modelled and described by four error parameters. The RELM consists of three bearings adding the total amount of error parameters to twenty-four. The addition of adding the bearing inaccuracy to the algorithm increased the accuracy by going from form ± 5.10 µm to ± 4.58 µm. Further increasing the accuracy by 10.2%.

The spacing inaccuracy of the rotary encoders was smaller than the overall achieved accuracy of the RELM. Modeling this inaccuracy therefore showed no improvement in overall accuracy of the RELM.

Error Parameter Mapping

If the only parameters that influence the inaccuracy of the RELM were dimensional and bearing errors the algorithm made complete by solving the error parameters would exactly describe the behaviour of the RELM. There are three remarks regarding this subject.
Firstly the calibration points were generated using a NC-machine tool. This NC-machine tool itself has a natural inaccuracy and therefore the calibration points have an inaccuracy which also influences the accuracy of the error parameters and therefore also influence the accuracy of the RELM.
Secondly because the error parameter algorithm is incomplete the error parameters found using calibration points close to each other do not accurately describe the whole measuring range of the RELM. This would be the case if the error parameter algorithm was complete.
Thirdly it is impossible to further decouple error parameter influences and even if this would be possible and the error parameters were found the increase in accuracy of the RELM would be minimal.

Because the error parameter algorithm is incomplete the spacing of the calibration points influences the error parameters. To be able to use the whole measuring range of the RELM a new approach was developed.

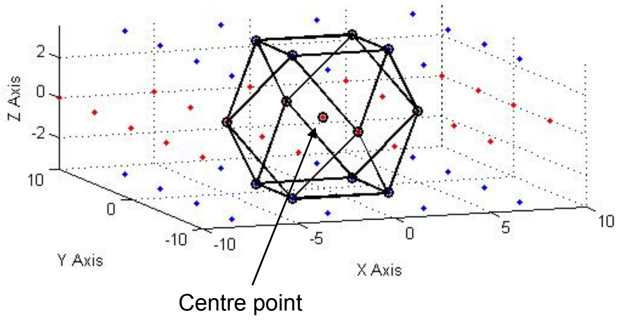

Figure 3. Error Parameter Mapping volume

Instead of using one set of error parameters for the whole measuring range different sets are used dependant on the tool path. The measuring range of the RELM is divided into small volumes. For each volume the error parameters are calculated, by using calibration points on the boarder of each volume. The centre point of each specific volume plays a crucial roll in this approach. When calculating the position of the steel ball during a measuring operation, the error parameters are used of that volume that has the smallest distance from it's centre point to the position of the steel ball. This developed method is called Error Parameter Mapping.

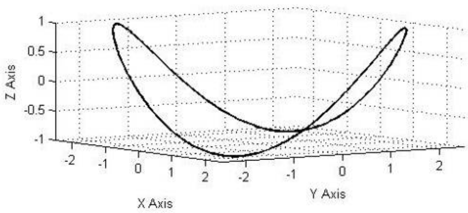

Figure 4. Three dimensional tool path

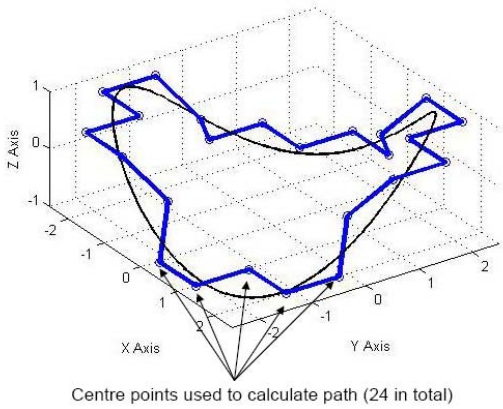

Figure 5. Path measured with using Error Parameter Mapping principle

Error Parameter Mapping using dimensional and bearing inaccuracy showed a slight decrease in accuracy of the RELM being ± 5.03 µm Two remarks can be made on this account.

Firstly is now is possible to use the whole measuring range of the RELM.

Secondly the volumes used for calculating the error parameters using the Error Parameter Mapping principle were smaller than the volumes used to calculate the influence of dimensional and bearing error parameters. Because of the inaccuracy of the generated calibration and the incompleteness of the error parameter algorithm there is an optimum between the spacing of the used calibration points. Further research is needed to find this optimum.

Conclusion

An algorithm has been made that includes dimensional and bearing inaccuracies of a three dimensional measuring device.

The principle of Error Parameter Mapping was developed enabling measuring any three dimensional tool path with an accuracy of ± 5.03 µm.

This is an increase of accuracy of the RELM by a factor 69 as the initial accuracy was ± 349 µm.

Recommendations

My recommendations for further research is to find the optimum spacing of the calibration points used to solve the error parameter model. Use a different device, with higher accuracy than an NC-machine tool to generate the calibration points used to solve the error parameters. This will definitely have an extra increase in the accuracy of the RELM as at this point it limits further increase in accuracy. A hardware recommendation would be to change the incremental rotary encoders by absolute rotary encoders. This would have the advantage that the error parameters would only have to be determined once, because the absolute positions of the calibration points would be fixed.